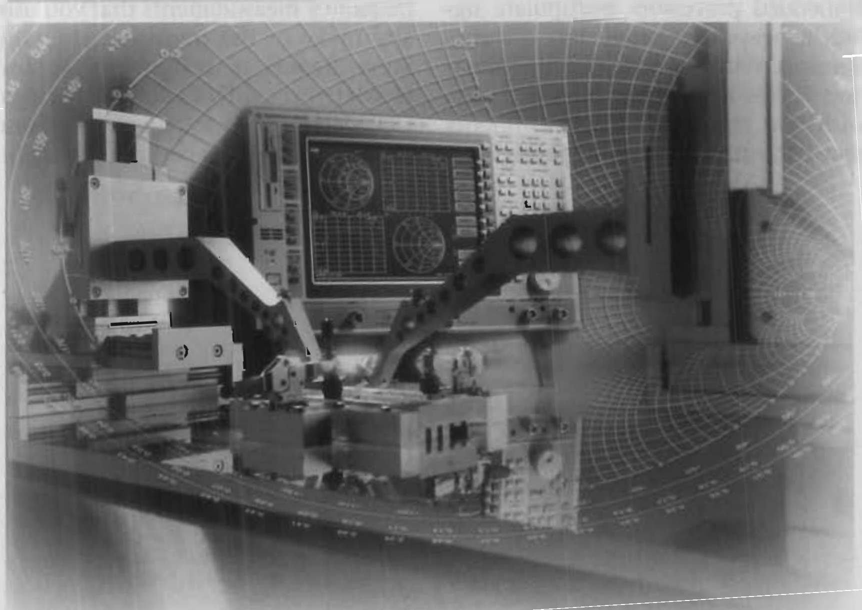
The frequency domain: A WHOLE 'NOTHER WAY OF THINKING

As signals move faster and faster, familiar time-domain measurement tools can't always keep up. Making a transition to frequency-domain tools can help, but it puts you in territory you may not have visited since you left school.

DAN STRASSBERG, SENIOR TECHNICAL EDITOR



The ZVR family of RF VNAs (manufactured by Rohde & Schwarz and sold in North America by Tektronix) includes models that cover frequencies as high as 8 GHz. The analyzers offer automatic calibration. Some units can simultaneously connect to more than two ports of the unit under test.

If you're like most designers of digital, analog, and mixed-signal circuits, you've spent most of your professional life working in the time domain. Of course, you know about the duality of the time and frequency domains—that there is a frequency-domain description for any signal you can describe in the time domain. And you know that multiplication in either domain is equivalent to convolution in the other. Still, nearly everything you know about signal behavior is couched in time-domain terms. Dealing with frequencies high enough to outstrip the capabilities of such familiar time-domain instruments as general-purpose oscilloscopes requires you to think in decidedly unfamiliar ways.

The idea of working at gigahertz frequencies requires no great leap of faith. Microprocessor clock rates are already within a holler of 1 GHz, and external-bus speeds are not too far behind. Most modern general-purpose oscilloscopes, even the few whose bandwidths exceed 1 GHz, cannot adequately display 1-GHz-repetition-rate digital signals. To render a decent picture of such a signal, your scope should have a –3-dB bandwidth of at least 3 GHz and, preferably, 5 GHz. Although you can find such scopes, they are specialized units.

There is, however, a group of EEs who have long dealt with signals at fre-

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quencies high enough to make direct observation of waveform details impossible. For over half a century, microwave engineers have dealt almost exclusively with such signals. As did their predecessors (the RF engineers of the '30 and '40s), microwave engineers have to measure, design, and *think* in the frequency domain.

Thinking in a new language

The differences between time- and frequency-based thought processes can be profound. Frequent *EDN* contributor Jim Williams of Linear Technology (www.linear.com) likens communication between microwave engineers and lower-frequency-circuit designers to communication between speakers who are each fluent in a different language. Each speaker *thinks* in his or her native tongue. To understand the speaker, the listener must laboriously translate what he or she has heard. Or, to speak the listener's language, the speaker must translate what he or she is about to say.

Over the years, you've built up a bag of tricks that you use so instinctively, you don't even think about it. Take, for example, when you use a digital scope to observe a nearly sinusoidal signal. If the amplitude seems to vary at a low frequency, you instinctively adjust the sweep speed. If the variation disappears at higher sweep speeds or significantly increases in frequency at lower sweep speeds, you can be pretty sure that the real signal contains no such variations. What you're looking at is aliasing, the result of unintentional undersampling. Without comparable experience in frequency-domain measurements, you can become the victim of the same sort of misleading information.

Even the improvements that manufacturers have made in instruments over the past 10 or 15 years can raise questions about the validity of measurements. In the "old days," instruments were simple enough that you could draw block diagrams of most of the instruments you used. Sure, such diagrams might have missed some of the finer design points, but you were pretty sure of the nature of the circuit blocks through which signals passed on the way from the probe to the display.

Those days are gone. Most of today's instruments are far more complex. Embedded processors manipulate signals in ways that often defy comprehension. Williams feels that this situation leaves instrument manufacturers with two choices: Build instruments that cannot produce misleading outputs or produce manuals (or instruments themselves) that warn you when you are using the instrument in ways that might mislead you.

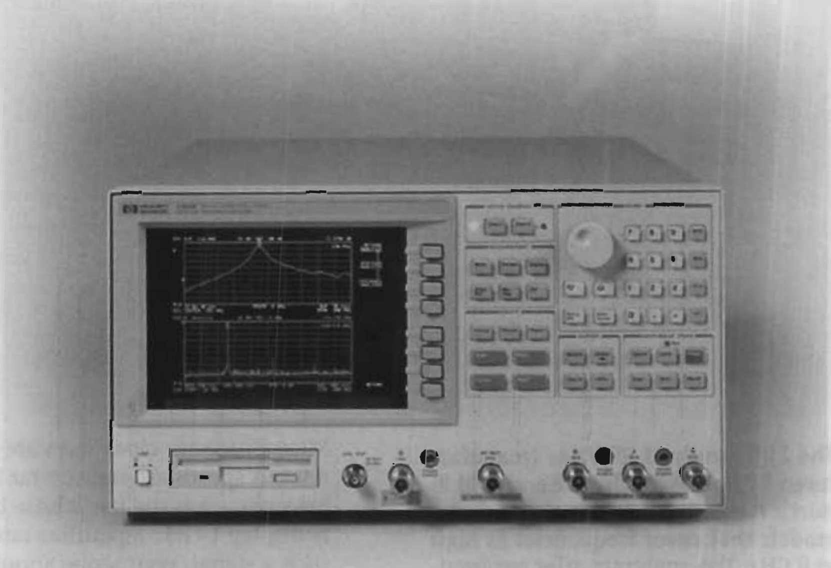
Few instrument manufacturers believe that either approach is practical except in isolated cases. For example, scope manufacturers have offered scopes that attempted to warn users when the sampling rate was low enough relative to the signal frequency that aliasing could occur. Such a feature, if it worked reliably, would have eliminated the aliasing problem described in the earlier example. However, features that manufacturers include to detect questionable operating conditions can further complicate already complex designs. In addition, unless the features are completely reliable, they can give users a false sense of security.

Complexity affects credibility

Modern instruments' complexity affects both frequency- and time-domain devices. Still, some problems are characteristic of the kinds of high-frequency measurements that you usually make in the frequency domain. Steve Roach, a design engineer at Hewlett-Packard's Colorado Springs, CO, Electronic Measurements Division facility, points out a particularly impor-

@a glance

- Although you understand the duality of the time and frequency domains, your first frequency-domain-measurement experience can reveal gaps in your practical knowledge.
- Before you start to believe your frequency-domain measurements, learn the effects of bending, crushing, and kinking the cables in your setup.
- Because they measure phase as well as amplitude, vector network analyzers (VNAs) can do much more than characterize components at high frequencies.
- By using inverse FFTs, VNAs can develop time-domain presentations from data they acquire in the frequency domain.



The HP 4396B RF VNA covers 100 kHz to 1.8 GHz as a VNA and an impedance analyzer; the unit can also function as a spectrum analyzer from 2 Hz to 1.8 GHz.

tant conceptual difference between low- and high-frequency circuits. In low-frequency circuits, elements are lumped; in high-frequency-circuits, you must think of the elements—even the simple passive components—as distributed. For a closer look at Roach's views on measurements in the two domains, (see **sidebar** "To see the whole picture, work in both domains").

Although matching the load impedance to the source impedance is sometimes important in low-frequency circuits, standing-wave ratio (SWR), a consequence of impedance mismatches in high-frequency circuits, has no low-frequency counterpart. There is, however, a time-domain equivalent to SWR: reflection coefficient, ρ. Because reflections and standing waves are manifestations of high-frequency networks' distributed nature, neither ρ nor SWR figures in the analysis of lumped-element (that is, low-frequency) networks.

Morris Engelson, the principal designer of many spectrum analyzers, makes a surprising point. His company, JMS Inc, consults on high-frequency-measurement and electromagnetic-compatibility problems and conducts training seminars on these subjects throughout the United States. Engelson says that many engineers who work only in the time domain are unaware of the most basic underpinnings of information theory. These engineers, he says, don't even understand that, to transmit information, a signal must contain more than one frequency.

Sidebands exist even in signals that you modulate in the most primitive way: by keying a sinusoidal carrier on and off. In theory, a signal that contains only one frequency is a sine wave that started at time=minus infinity and goes on unchanged forever. Such a signal carries no information.

Scopes are unique

Nearly every EE readily acknowledges the oscilloscope's role as the most

TO SEE THE WHOLE PICTURE, WORK IN BOTH DOMAINS

STEVE ROACH

Ever-higher signal speeds are forcing engineers to use frequency-domain instruments, even in digital systems. However, the fact that general-purpose scopes are too slow to view the signals isn't driving this trend. Granted, the scopes in most labs are too slow. So to work with, say, a 1-GHz serial peripheral bus (coming soon to a motherboard near you), engineers need microwave scopes with high-frequency probing. So why do engineers need frequency-domain analysis and measurement techniques where they didn't need such techniques before? Here is my view.

You can separate the new high-frequency systems that engineers face into two types: narrowband high-frequency systems (wireless communications), in which the signals are naturally expressed in frequency-domain terms, and wideband high-frequency systems (digital computers and networks), in which the signals are naturally expressed in time-domain terms. Narrowband communications systems are still best served with frequency-domain methods, but very-high-speed digital systems are forcing designers to leave the familiarity of the time domain. Why? Because frequency-domain methods add information to an engineer's understanding of a system, not because oscilloscopes are too slow to view the signals.

For example, jitter on clocks is now a serious problem in high-speed digital systems. (Hardly anyone knew jitter existed in the 10-MHz buses of the early '80s.) A microwave scope easily shows you the jitter on a 1-GHz clock, but a spectrum analyzer can add a great deal of information to your understanding of the jitter sources. Network analyzers are helpful in characterizing components and transmission lines in high-speed digital systems, often for building simulation models.

Time-domain-reflectometry (TDR) capabilities, such as those of microwave scopes, are indispensable because TDR actually tells you where in space and time a transmission line is compromised. Today, however, network analyzers that use inverse Fourier transforms to convert results into the time domain provide similar information, just as scopes that compute FFTs perform many spectrum-analyzer functions. A plus for spectrum and network analyzers is the extraordinary dynamic range they bring to their measurements. This dynamic range far exceeds that of oscilloscopes.

More than double your insights

The really powerful approach to dealing with the new ultrafast digital systems is to equip your lab with easy-to-use 500-MHz to 1.5-GHz scopes for troubleshooting and casual characterization; a 20-GHz microwave scope with TDR for precise characterization; a spectrum analyzer for measuring jitter and interference; and a network analyzer for characterizing amplifiers, components, and transmission lines.

Sequential-sampling, 20-GHz-bandwidth scopes are the next class of scopes that will see use by most engineers who work on gigahertz digital systems. If you work with digital signals to a few gigahertz, such scopes will serve you well, even when you use probes to acquire the signals. A 20-GHz microwave scope with TDR costs about the same as a 6-GHz network analyzer, and these instruments complement each other nicely. Beyond these instruments lie 50-GHz scopes and 40+-GHz network analyzers. For many engineers, working at these frequencies will require advanced training in microwave techniques. However, most of us still have a few years before our designs force us to make that adjustment.

To summarize, high frequencies are not yet driving engineers away from oscilloscopes and from the time domain. Rather, they are finding that you need frequency-domain methods and measurements to complement time-domain methods. The combination adds crucial information and fills out your understanding of your high-speed system.

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Frequency-domain tools

important tool for investigating the time-domain behavior of signals. Years ago, someone whose identity has long since been forgotten observed that electrical engineers are unique among scientific and technical professionals in possessing such a valuable instrument. No other discipline has a tool that provides such deep and immediate insights into the operation of fundamentally invisible processes.

Although scopes with bandwidths greater than 1 or 1.5 GHz are much less common than units whose bandwidths are 1 GHz or less, wider bandwidth scopes do exist. Both Hewlett-Packard and Tektronix offer units with bandwidths as high as 50 GHz. These ultrawideband scopes are specialized, and most are costly. The flagship models, HP's 54750A and Tektronix's 11801C, offer the versatility of plug-in sampling heads. The 54750A with two 54752A two-channel 50-GHz plug-ins (a total of four channels) costs \$49,000. The 11801C with four SD32 50-GHz sampling heads costs \$52,500. Tektronix's TDS 820, a two-channel scope that offers 6-GHz-bandwidth (8 GHz in models that sacrifice the ability to view pretrigger events), costs \$22,040.

Despite their enormous bandwidths, these scopes acquire signals rather slowly. The reason for the relatively slow acquisition is that these instruments use sequential-equivalent-time sampling and not random sampling. Most general-purpose digital scopes switch to random sampling when they can't sample signals fast enough in real time. Although it has never matched the bandwidth of sequential sampling, random sampling allows faster acquisition.

Sequential equivalent-time-sampling scopes acquire one signal point each time the scope triggers. Each point occurs incrementally later in the waveform than its predecessor. This type of sampling translates the sampled signal's frequency spectrum downward—usually so that it falls within the audio-frequency range. Sequential sampling is a form of intentional undersampling and is a mathematical first cousin of the modulation process known as heterodyning. Heterodyning converts high carrier frequencies to lower intermediate frequencies in most radio receivers and in "preselectors," which extend the frequency ranges of instruments such as digital counters.

Whether you use sequential sampling or heterodyning, a key require-

With a pair of wideband two-channel plug-ins, the HP 54750A sequential-equivalent-time-sampling digital oscilloscope can capture four 50-GHz-bandwidth signals.

FOR MORE INFORMATION...

For information on ultrawideband digital oscilloscopes and frequency-domain measurement products such as those discussed in this article, circle the appropriate numbers on the Information Retrieval Service card or use EDN's Express Request service. When you contact any of the following manufacturers directly, please let them know you read about their products in EDN.

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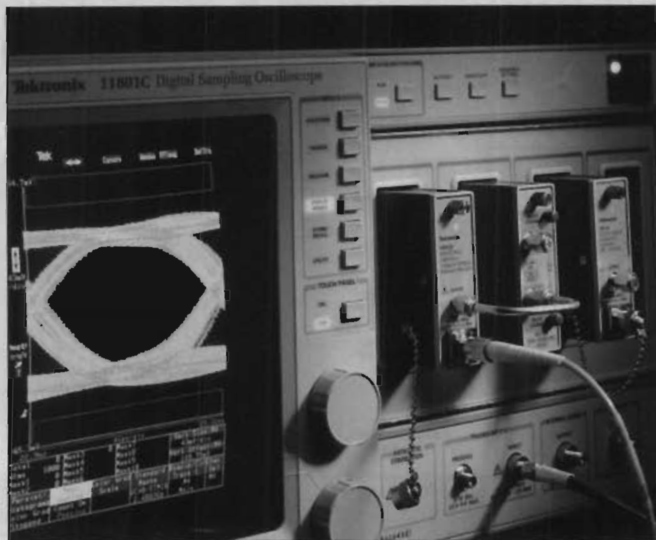

The 11801C sequential-equivalent-time-sampling digital oscilloscope from Tektronix can accept four single-channel plug-ins. The SD32 plug-in samples 50-GHz-bandwidth signals.

ment for proper downconversion is that the incoming signal must persist and not change in character for many carrier-frequency cycles. (In mathematical terms, the signal must be "stationary," that is, its probability-density function must not change during the measurement.) The instrument takes advantage of the signal's repetitive nature to extract crucial information.

Another way to think about sequential sampling and heterodyne down-conversion is to consider both as ways to use additional measurement time to extract more precise timing and amplitude information from a repetitive signal. Sequential sampling lets you use extra measurement time to, in effect, slow down real time for repetitive signals. Moreover, most sequential-sampling scopes' ADCs offer higher resolution than general-purpose scopes. However, if time-domain techniques offer no good way to directly measure the signal properties, you can often reconstruct those properties from a series of frequency-domain measurements. The key is to preserve the relative phases of the various frequency components.

Phase as well as amplitude

When you mention frequency-domain signal-analysis tools, most people automatically think of spectrum analyzers. These people usually consider network analyzers to be highly specialized frequency-domain instruments that characterize transfer functions and impedances. Unlike spectrum analyzers, network analyzers generate the stimulus signal for the unit under test (UUT). This stimulus is a sine wave at the frequency to which the analyzer is tuned. Usually, a test involves several measurements, each at a different frequency.

Still, most spectrum analyzers don't provide phase information, whereas many network analyzers do. That is, *vector* network analyzers (VNAs) do. Therefore, you can argue that VNAs are more general than spectrum analyzers. Indeed, a few VNAs also function as spectrum analyzers. In the spectrum-analysis mode, such dual-function instruments do not provide a stimulus signal. Some VNAs also display the time response of the network under test by using inverse Fourier transforms to derive the time response from the acquired frequency-domain data.

A comparison between the time- and frequency-domain techniques for measuring the settling time of a high-speed amplifier is instructive. Using the normal time-domain technique, you measure settling time by viewing the difference between the amplifier's instantaneous output and the ideal output at t=infinity. If the measurement circuits become overloaded, the measured settling time can be grossly incorrect. Therefore, you must carefully limit the difference signal's peak voltage.

Deriving the transfer function from frequency-domain measurements can actually be easier—especially if the network analyzer does the math for you. There is no need to specially condition the amplifier output. A key question is whether the nonlinearities that the device under test introduces invalidate superposition. The ability to determine the time response from frequency measurements depends on superposition. When the amplifier slews, it saturates; superposition doesn't hold when the amplifier is saturated. Also, thermal effects on settling differ in the two measurements. Still, Williams reports excellent correlation between classic and VNA-based settling-time measurements on a couple of wideband amplifiers.

Like 50-GHz sampling scopes, RF VNAs don't come cheap. For example, HP's 8752C, equipped to make 6-GHz measurements and to convert frequency-domain measurements into time-domain responses, costs $36,250. (The lower end of the 8752C's frequency range is 300 kHz, but some VNAs with similar upper frequency limits can work at frequencies as low as 9 kHz.) A step attenuator adds $1020 to the price, and a 6-GHz-bandwidth passive probe adds $995. The instrument's tuned receivers provide a dynamic range as high as 110 dB. The unit's color display presents information on two channels, providing simultaneous views of the UUT's magnitude and phase responses.

A network analyzer includes a signal source. The 8752C's synthesized source produces +5 to –20 dBm (+10 to –85 dBm with the step-attenuator option) and can sweep and frequency-hop in a variety of modes.

In the minds of some engineers, the term "network analyzer," conjures up images of high frequencies, waveguides, and other microwave "plumbing." Indeed, some network analyzers do work at microwave frequencies that go well beyond the range of even the fastest sampling scopes. However, your need for microwave paraphernalia is more a function of the frequencies at which you work than of the instruments you use. If a 6-GHz sampling scope is appropriate for your measurements, your breadboards demand as much care as they would if you measured their performance with a 6-GHz VNA.

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In pc boards that contain digital circuits clocked at 1 GHz, you will probably work with strip line and coaxial cables rather than with waveguides. Most likely, you will create the strip line within your boards by surrounding inner-layer conductors with ground planes. Ideally, you'd like to create a constant-impedance environment—that is, an environment in which all of the cables have the same characteristic impedance (Z_0) and are terminated in Z_0. In such an environment, there are no standing waves and no pulse reflections.

Difficult environments

Constant-impedance environments, though ideal for network analyzers, are difficult to realize on pc boards. Moreover, the Z_0 of pc-board traces almost always differs from the value (usually 50 or 75Ω) for which the analyzer was designed. Network analyzers are surprisingly forgiving, however. First, you can usually purchase adapters that match the analyzer inputs and outputs to standard Z_0 values that differ somewhat from those for which the analyzer was designed. Second, you can calibrate for impedance mismatches and discontinuities.

Many new analyzers incorporate sophisticated calibration facilities that reduce the number of calibration steps and reduce to only a minute or so the time that calibration requires. An example of a VNA family that offers such facilities is Rohde & Schwarz's ZVR (available in North America from Tektronix). Prices for these units, some of which cover frequencies as high as 8 GHz, begin at less than $35,000. Some of these units incorporate more than two measurement channels. The additional channels allow you to fully characterize many multiport networks with a single set of measurements.

It is a bad idea to become too dependent on VNA calibration facilities, regardless of how sophisticated they are. The idea that calibration can "make everything right" can encourage a dangerous false sense of security.

Learn the territory

HP's Roach urges engineers who are new to network analyzers to spend a few days familiarizing themselves with how the instruments behave in the presence of nonideal electrical environments. Create a trial setup. Bend the cables. Crush them. Introduce intentional kinks. Then see what happens when you use calibration to remove the effects of this abuse. Only by becoming familiar with the instruments' behavior in such nonideal situations will you be able to tell when the instrument is providing meaningful results and when setup problems are leading you astray.

If you intend to use a spectrum analyzer, see what effects you can measure both in the time domain with a scope and in the frequency domain with the spectrum analyzer. Try measuring the jitter of a high-frequency clock. In the frequency domain, increasing the jitter broadens the discrete-frequency spikes that make up the signal's spectrum. See if you can determine the magnitude of the spectral-line spreading that results from a known increase in jitter.

JMS' Engelson advises spectrum-analyzer users that one all-too-common way of obtaining misleading information from a spectrum analyzer is to accidentally select a sweep time that coincides with gaps in the signal you are characterizing. Most spectrum analyzers sweep fairly slowly through the frequency range they are characterizing. If a frequency component is not present when the analyzer is tuned to it, the component doesn't appear in the displayed spectrum.

Real-time spectrum analyzers

A way around the problem of disappearing or invisible frequency components is to use a real-time spectrum analyzer (RTSA), such as Tektronix's new 3066. Compared with conventional swept-frequency analyzers, RTSAs downconvert wider segments of the frequency spectrum (5 MHz for the 3066) and make broadband sweeps by hopping among frequency bands. RTSAs use FFTs to derive the fine structure of the frequency components in the downconverted band. Engelson says that, although some RTSAs are portable and relatively inexpensive, the useful ones are larger and cost more. The 3066 costs $43,500. However, unlike some earlier high-quality RTSAs, the 3066 comprises only a single unit.

When using a spectrum analyzer, you also have to learn to distinguish signals that the UUT produces from signals that originate elsewhere. Roach reports being momentarily puzzled by a 930-MHz signal that his spectrum analyzer apparently showed coming from the wideband amplifier under test. The fact that the signal appeared and disappeared roughly once per second provided the tip-off that the signal originated in a wireless LAN and not in the UUT.

Other ways to obtain misleading information from a spectrum analyzer include failing to account for the calibration of the instrument's detector circuit. Most spectrum analyzers use peak detectors that produce correct power readings when the signal is sinusoidal. A sinusoidal signal's power and rms voltage are 3 dB lower than the values corresponding to a dc voltage that equals the peak ac voltage. With random noise, the ratio of peak to rms voltage or power is greater still—approximately 15.5 dB. This value also closely approximates the peak-to-rms ratio of digital-communication systems' quadrature-amplitude-modulated signals. EDN

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